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Low-Energy Ion Mass Spectrometer on CRRES

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Scientific Objectives

THE low-energy ion mass spectrometer (IMS-LO) (ONR-307-8-1,2) is part of the SPACERAD[1] payload on the CRRES[2]. IMS-LO is designed to measure the composition of plasmas that are the sources of radiation belt particles, and to provide data on the origin and acceleration processes of these plasmas. To achieve these objectives, the instrument measures energy and mass spectra covering the ranges of $E/q =$ 0.11 − 35 keV/e and M/q from 1–32 amu/e with good coverage of pitch angles throughout the CRRES orbit.

Measurement Techniques

The IMS-LO-1,2 instruments on CRRES rely on essentially the same design that was successfully implemented with previous Lockheed instruments on SCATHA (launched January 1979) and S3-3 (launched July 1976). Improvements have been made with each version of the instrument in range of coverage, resolution, and operating flexibility.

IMS-LO-1 and IMS-LO-2 are identical instruments which are mounted on the aft surface of the spacecraft with their look directions at 135 and 105 deg to the spacecraft $+Z$ axis. In the spacecraft X-Y plane they are both at 45 deg from the $+X$ axis, clockwise viewing in the $+Z$ direction. CRRES spins about the Z axis with $+Z$ oriented sunward. The look directions of the instruments were chosen to maximize coverage of fluxes near the magnetic field line direction thoughout the mission. Each instrument performs ion-composition measurements in the energy per charge range 0.11–35 keV/e and the mass per charge range 1–32 amu/e. The energy range, which is covered by 45 energy steps, is broken into three contiguous parts (j = 0,2), each consisting of 15 energy steps (i = 0,14). The mean energy per charge E_{ij} of ions on the ith step of the jth part is given by

$$E_{ij}\ (\text{keV}) = 0.109 \times (1.14008)^{(i + 15j)} \qquad (1)$$

The three parts of the energy coverage are sampled in parallel by three separate analyzer and sensor units ("heads"). At the completion of each 15-step sequence, the background counting rate is measured for each sensor head. The mass range (1–32 amu/e) is covered by 32 steps. Alternatively, the spectrometer can be commanded to a heavy-ion mode as described in the section below on operating modes and control. In addition to ion measurements, each of the two instruments monitors the background electron flux at four fixed energies. The electron channels are described in a separate section below.

Ion Optics

Each of the IMS-LO mass spectrometers consists of three analyzer heads which measure ions in a different portion of the E/q range from 0.11–35 keV/e. One of the analyzer heads is illustrated in Fig 1. Each analyzer consists of four sections: a collimator, a velocity filter, an energy analyzer, and a channel electron multiplier detector.

Ions enter the instrument through the collimator that provides an acceptance cone of approximately 5-deg full width. Following collimation, the ions enter the crossed electric and magnetic field velocity filter (Wien filter), which acts as the mass analyzer (MA). Its magnetic field is fixed while the crossed electric field is varied according to the value of E/q and M/q being sampled. The fields are oriented so that the electric and magnetic forces on an ion are in opposition, and

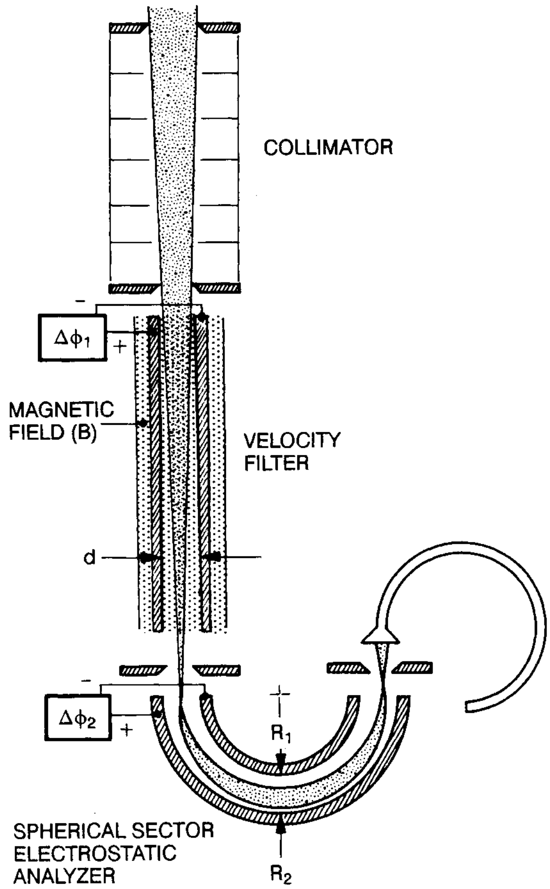

Fig. 1 Ion mass and energy analysis optics for the low energy ion mass spectrometer.

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the electric field is chosen so that there is no net force on an ion of the desired mass and energy, allowing it to pass through the MA in a straight trajectory. The MA magnetic fields in the three heads are nominally 445, 1211, and 3304 G. The electric field plates of the MA are driven symmetrically and the voltages for a given mass selection scale as the square root of the ion energy which is determined by the voltage applied to the electrostatic analyzer. The maximum MA plate potentials in the three heads, corresponding to the minimum ion mass and the maximum energy per charge sampled by the head, are nominally, ± 35, ± 253, and ± 1850 V for the normal mass range and a factor of six lower for the heavy-ion mode. All three heads are driven by a common high-voltage power supply and a divider network that provides the different ranges required.

Following the velocity filter, ions are bent 180 deg in a hemispherical sector electrostatic analyzer (EA) which is angle focusing and energy dispersive. As with the MA, the EA plates in all three heads are driven by a common power supply and a divider network. The ratio between consecutive values of the logarithmically spaced energy steps is approximately 1.14, and there are 15 energy steps assigned to each head. Thus, the energy per charge being simultaneously sampled by the three heads are spaced by a factor of approximately 7, with the first head covering from 0.11–0.68 keV/e, the second from 0.78–4.9 keV/e, and the third from 5.6-35 keV/e. The EA plate separation in the high-energy head is reduced from that of the other two heads in order to achieve the desired energy range without the need for excessively high voltages. After exiting the EA, ions are postaccelerated by 1 kV, to improve detection efficiency, and enter the channel electron multiplier detector.

The stepping of the EA and MA is coordinated under digital control in a number of modes as described in the following section. Each sample of a particular mass-energy value takes 64 ms. There is a 12-ms deadtime at the beginning of each sampling period to ensure complete settling of the analyzer power supplies, even in the worst-case transitions.

In addition to the energy steps just described, there is an additional setting in which each of the three heads measures background counts. The background measurement is performed by disabling the MA power supply and setting the EA power supply to step 4. As the MA power supply decays toward zero, the analyzers pass continually higher masses. Following the 12 ms deadtime, the background channel is sampling mass per charge values well above those of ambient ions and measures the instrument background response only.

Electron Detectors

Each of the IMS-LO instruments contains a set of four broadband, fixed-energy electron detectors, as shown in Fig. 2, which are used to monitor electron fluxes between 50 eV and 25 keV. Electrons entering one of these instruments are collimated to a 5 deg acceptance cone and pass through an aperture that sets the geometric factor. The electrons are then bent 180 deg in a magnetic analyzer and pass through an exit aperture that sets $\Delta E/E$ before entering the channeltron sensor. The $\Delta E/E$ for each detector is 50% and the central energies of the electron channels on IMS-LO-1 and IMS-LO-2 are interleaved, providing a total of eight channels with central energies from 0.067–20 keV. The electron detectors accumulate for 512 ms, providing samples approximately every 6 deg of spacecraft spin.

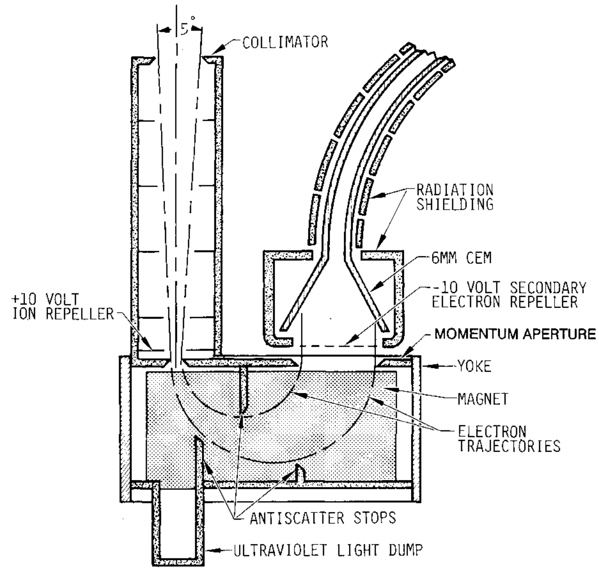

Fig. 2 Schematic of a single magnetic electron analyser.

Operating Modes and Control

There are two basic submodes of operation of the mass spectrometers: SWEEP and LOCK. Each of these submodes takes 32.768 s to complete, approximately one spacecraft rotation.

The LOCK submode maximizes resolution in time and pitch angle by concentrating on selected masses. The instrument is locked on the selected mass per charge while stepping in energy. Each energy step and background are sampled for 64 ms and the three sensor heads together acquire a 45-point energy spectrum in 1.024 s, approximately 12 deg of spacecraft rotation. In the LOCK submode, 32 consecutive energy spectra are acquired at the selected mass before the instrument moves into the next submode.

The SWEEP submode examines the mass spectrum in more detail but with reduced resolution in time and pitch angle. In this submode, the instrument acquires a mass spectrum at each energy step by sweeping through all 32 mass steps while the energy is held steady. Each mass step is sampled for 64 ms and a full mass spectrum is acquired in 2.084 s. The complete mass-energy spectrum, 32 mass steps at each of 45 energy steps together with 32 background measurements, is acquired in 32.768 s.

Eight submodes are combined to form the three basic modes of operation; LOCK-ONLY, SWEEP-ONLY, and SWEEP-LOCK. As the names imply, LOCK-ONLY consists of LOCK submodes only, SWEEP-ONLY is composed of SWEEP submodes, and SWEEP-LOCK alternates between SWEEP and LOCK. In either the LOCK-ONLY or SWEEP-LOCK modes, the mass steps used in the LOCK submode are taken sequentially from four values that are held in the instrument memory. These values may select any four of the 32 M/q steps and correspond to any four ion species; for instance, H^+, He^+, He^{++}, O^+; or H^+, O^+, H^+, O^+. IMS-LO-1 and IMS-LO-2 are commanded independently so that it is possible to have the two instruments operating in different modes simultaneously. The operating mode and LOCK mode mass steps can be selected by command. Initially, both instruments were operated in the SWEEP-ONLY mode while their performance was assessed and on orbit measurements of mass peak shapes were made. Subsequently, both instruments were commanded into the SWEEP-LOCK mode with the LOCK mode steps set for H^+ and O^+.

In addition to the normal range of mass coverage, the instrument can be commanded into a heavy ion mode for use during chemical release experiments. In this mode, the MA and EA voltages are reduced by a factor of six, scaling the M/q coverage upward and the energy downward to give an operating range of 5–250 amu/e and 0.02–5.8 keV. During barium releases, one of the instruments has been operated in the heavy ion SWEEP-LOCK mode to search for Ba^+. When lithium releases were made one of the instruments was operated with the LOCK mode steps set for Li^+. The other instrument remained in the normal mode of operation to continue to monitor ambient plasma.

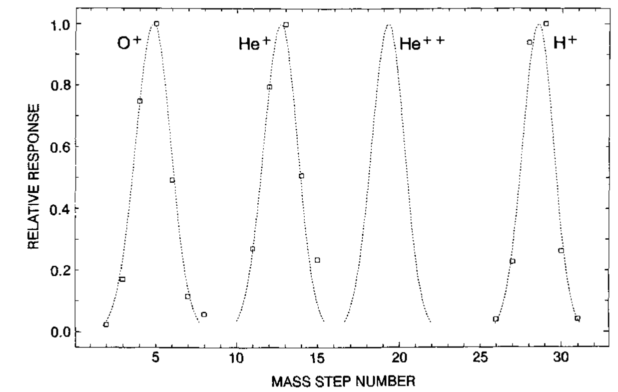

Fig. 3 Mass peak shapes at a representative energy step, from on-orbit data.

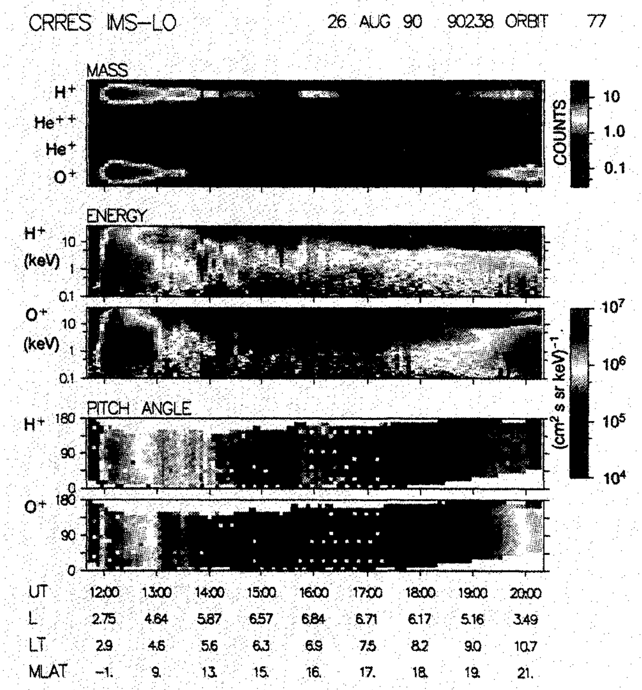

Fig. 4 Summary plots of data from one ion mass spectrometer.

The discriminator threshold for each detector is set by command to one of four values. A special calibration cycle will be commanded periodically which locks on a selected mass step and sequentially steps through the thresholds to monitor the channel electron multiplier gain. In addition, the calibration command may optionally enable pulses at a known rate to monitor performance of the signal processing electronics. The channel electron multiplier bias is command selectable to one of four values to compensate for possible channel multiplier gain degradation over the life of the mission.

Calibration

A good understanding of the characteristics of the mass spectrometer's response to ambient ions is necessary in order to interpret the data it obtains correctly, to optimize its operating modes, and to determine the correct ratios for the EA and MA voltage divider networks. Three approaches were used which provided complementary information on the spectrometer's characteristics. During the design phase, detailed ray-tracing studies provided a baseline description of the variation of the mass spectrometer's response to ions' energy, mass, and approach direction.

The flight instruments were individually calibrated in the Lockheed Palo Alto Research Laboratory mass spectrometer calibration facility in which they were exposed to monoenergetic beams of selected ion species. The detailed energy-mass response of each spectrometer head was investigated at a number of representative energies. At each energy, an ion beam of H^+ or Ne^+ at the selected energy was directed at the instrument and the EA and MA voltages varied in small increments to provide a dense mesh of measurements to characterize the response function.

Since the full response is dependent on approach angle and incidence position, as well as energy and mass, it was not practical to perform the huge number of individual measurements that would be needed with a monoenergetic beam to fully characterize all of the spectrometer's 45 energy steps. Instead, during an on-orbit calibration procedure, ambient ring current ions were utilized as a multi-ion isotropic extended energy source that could be relied on to fill the field of view of the spectrometer. With the instruments in SWEEP mode, mass spectra were acquired at all energy steps. These measurements provided relative response functions for common mass species at all energy steps. Figure 3 shows peak shapes obtained in this way near the middle of the head's energy range. The dashed lines represent inferred peak shapes whereas the marks show on-orbit data. Mass resolution in this type of instrument is dependent on mass and energy. The $\Delta M/M$ is lowest for H^+ at the low energy of each head and increases with increasing energy and mass. At the middle of the energy range, $\Delta M/M = 0.15$ for H^+ and $\Delta M/M = 0.35$ for O^+. In the heavy ion mode, $\Delta M/M = 0.16$ for Li^+ and 0.47 for Ba^+. The acceptance angle is approximately conical with a full width at 50% sensitivity of 5 deg. The 30 s satellite spin period results in a movement of the instrument of less than 1 deg during the 64 ms sample time. The instrument geometric factors are 4×10^{-4} cm²sr and $\Delta E/E$ of $\approx 10\%$ for the two lower energy heads. The narrower EA plate separation in the high energy heads results in a geometry factor of 2×10^{-4} cm²sr and $\Delta E/E$ of $\approx 5\%$.

The characteristics of IMS-LO are similar to those of its predecessors on S3-3 and SCATHA but it differs from the ion mass spectrometers on some other magnetospheric satellites such as ISEE-1, DE-1, and AMPTE/CCE. The sensitivity of these instruments[3] is substantially constant over their energy range, but their field of view and $\Delta E/E$ increase substantially at low energies whereas the sensitivity of IMS-LO is proportional to energy and its field of view and $\Delta E/E$ are constant.

Data Reduction

The IMS-LO instruments completed their initialization sequence and began normal operations on August 4, 1990. They are operating well and returning good quality data. Figure 4 displays an example of summary plot data from one of the spectrometerse. The summary plots provide an excellent overview of a whole orbit and display mass and energy spectra and pitch-angle distributions as a function of time. For these plots the data have been averaged over 262 s intervals. The upper panel shows mass spectra from the highest energy analyzer. This contains horizontal bands near the bottom and top which correspond to H^+ and O^+, respectively. Two faint intermittent bands corresponding to He^+ and He^{++} can also be distinguished. The next two panels display the pitch-angle distributions of H^+ and O^+. For each of these the flux has been sorted into 10-deg pitch-angle bins.

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